Modeling, Controls, and Applications of Community Energy Storage Systems with Used EV/PHEV Batteries

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***Abstract*-- This study presents the modeling and controls of a community energy storage system composed of repurposed used electric or plug-in hybrid electric vehicle (EV/PHEV) battery packs. The expectation is that the vehicular batteries will be replaced with a fresh battery pack by the original equipment manufacturers (OEMs) once their performance (storage capacity and peak power capability) decrease to its 80% of the initial performance. Community energy storage (CES) systems can be a feasible application of these after vehicle batteries due to economic and environmental reasons. These batteries, if their power electronic interfaces are controlled properly, can perform many grid support applications or provide grid ancillary services as will be detailed in this study.**

***Index Terms*— CES, Community Energy Storage, lithium ion, peak shaving, regulation, ancillary services.**

I. Introduction

Applications of energy storage systems in power systems has always drawn significant interest from energy storage manufacturers and power system experts. A key issue for mass-market acceptance has been capturing the applications that have benefit to cost ratios exceeding 1.0. In a recent study, single and synergistic benefits were examined for secondary use battery applications and a number of applications where energy storage will most likely fill a role were proposed [1]. The term "secondary-use" in relation to battery technologies refers to batteries previously utilized in electric vehicles, but are no longer considered viable for these vehicles and must either be recycled or repurposed for other applications.

Growing interest has appeared in the concept of applying these secondary use batteries in a distributed sense in conjunction with the smart grid. By distributing energy storage along many locations, these units could provide the same benefits as a centralized unit but with potentially more localized applications. Community energy storage (CES) is an example of such a system and has been described to have benefits that target shifting renewable generation and load peaks, providing uninterruptable power, local reactive power support, and grid services when aggregated with many units [2], [3]. Community energy storage is the utilization of an energy storage system between several residential homes and the transformer connecting the homes to the distribution feeder as shown in Fig. 1. The purpose is to buffer the distribution feeder from potential impact of renewable resources as well as new larger loads such as PHEV (plug-in electric vehicle) and EVs (electric vehicles.) As shown, an isolation switch is also present to sustain the residential homes for a short period during a system outage. These units have been generally slated to the size of 25kW with 50kWh of energy storage and can supply between 2 and 5 homes depending on the load [2], [3].

This paper is focused on the development of the power electronics interface and control for CES application. The specific applications discussed are: delivering peak shaving or increased load factor delivery at the residential level, providing potential regulation and spinning services via a signal received from a central control system (i.e., aggregator, utility, or ISO), providing voltage support through reactive power when required, and providing uninterrupted service. This paper will utilize data captured from occupied residential homes for simulation of the load and a lithium ion battery model to capture generation and charging characteristics.

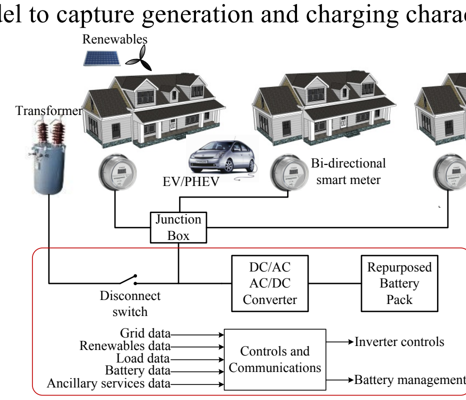

Fig. 1. CES unit supplying three homes.

II. System description

A. Residential Data

In conducting the analysis, residential data is needed to establish the basic variances in energy consumption. Oak Ridge National Laboratory has been collecting data from

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occupied homes in case studies to establish the benefits of retrofits in terms of energy efficiency. This data is collected on a one-minute time step and contains the subtle nuances of various loads switching on and off. An example the data set for a single home from Monday to Friday is provided in Fig. 2.

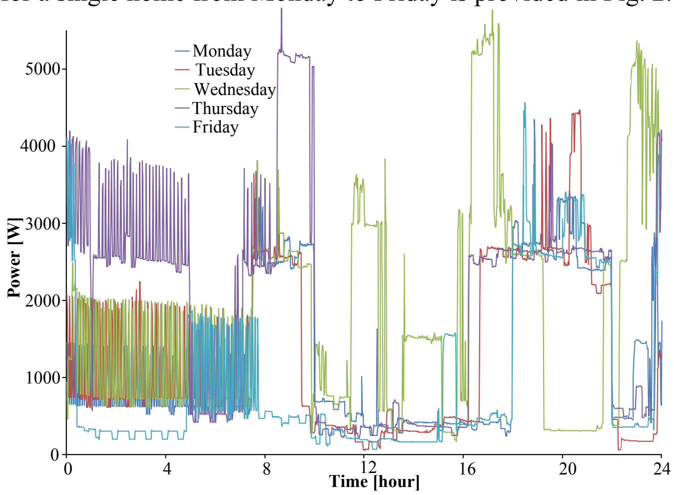

Fig. 2. Measured power levels for occupied home.

This data set shows that the residential homeowner often follows a consistent pattern of load usage. Two other home data sets were also examined. Statistical data, including the energy consumed during a single week, the maximum demand, average demand, and load factor is shown in Table I. Load factor is the average demand over the maximum demand and provides an indication on how well the utility's equipment is being utilized. Utilities would prefer to have a value of 1 for the load factor as the installed equipment is fully being utilized, however they must design based on the maximum demand [4].

TABLE I
HOME DATA

Characteristic Info	House 1	House 2	House 3	Total
Energy Usage (kWh)	204.5	1095.8	253.1	1553.4
Maximum Demand (kW)	10.2	18.5	5.8	23.3
Average Demand (kW)	1.2	6.5	1.5	9.2
Load Factor	0.12	0.35	0.26	0.395

The diversified demand for the 3 houses is provided in Fig. 3. This is the aggregated demand from the 3 separate homes and has been plotted for an entire week. Again, a periodicity is noticeable in the waveform. However, the diversified demand has a much higher load factor as compared to the single homes as shown in Table I. This diversified demand represents the load utilized in modeling. Using the power demand, a controlled current source has been implemented within the model that draws the corresponding current according to the measured voltage and expected power. Since only real power has been captured, the load is assumed to be at 0.9 power factor during the simulation runs.

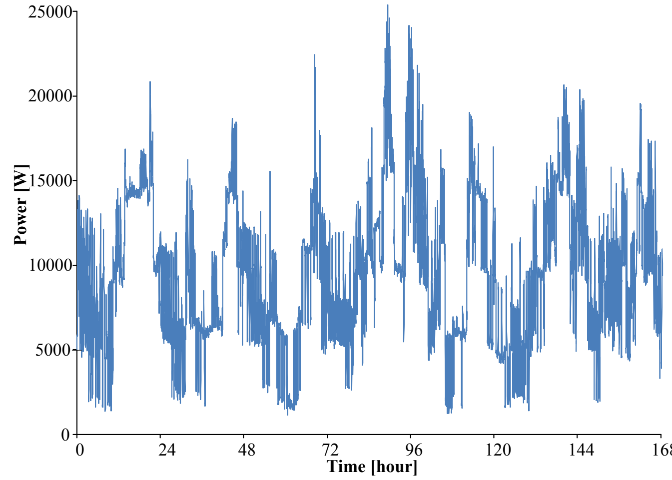

Fig. 3. Aggregated power of three homes.

B. Lithium-ion Battery Model

The battery model implements a generic dynamic model that can be parameterized to represent the most popular types of rechargeable batteries; i.e., Ni-Mh and Li-ion. The battery model is represented in Fig. 4. Charge and discharge modes of the Li-ion battery are expressed as equations (1) and (2), respectively.

$$f_1(i_b/s, i_b) = V_0 - K\frac{Q}{i_b/s+0.1Q}i_b - K\frac{Q}{Q-i_b/s}\frac{i_b}{s} + A.\exp(-B.i_b/s) \quad (1)$$

$$f_2(i_b/s, i_b) = V_0 - K\frac{Q}{Q-i_b/s}i_b - K\frac{Q}{Q-i_b/s}i_b/s + A.\exp(-B.i_b/s) \quad (2)$$

where V_b^* is the nonlinear battery voltage [V], V_0 is the open-circuit voltage [V], *Exp(s)* is the exponential region characteristics [V], *Sel(s)* is the mode of operation either charging (1) or discharging (0), as shown in Fig. 4, K is the polarization constant [Ah^{-1}], i_b is the battery current [A], i_b/s is the extracted or added capacity (integrated battery current) [Ah], Q is the maximum battery capacity [Ah], A is the exponential voltage [V], and B is the exponential capacity [1/(Ah)].

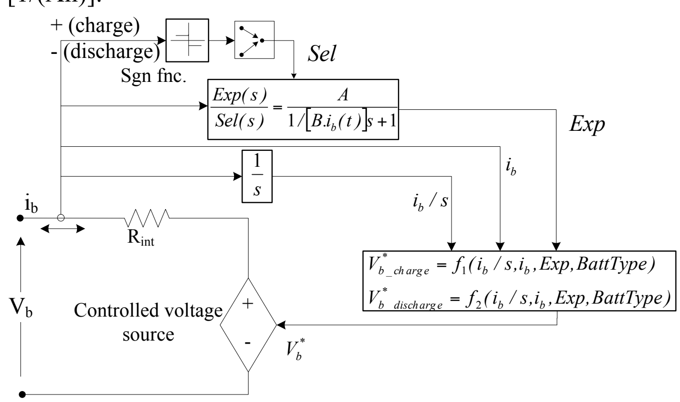

Fig. 4. Implementation of the battery model.

The battery model represents the characteristics of the selected particular battery type based on its charge/discharge characteristics [5], [6]. The battery discharge characteristics used in this study are represented in Fig. 5.

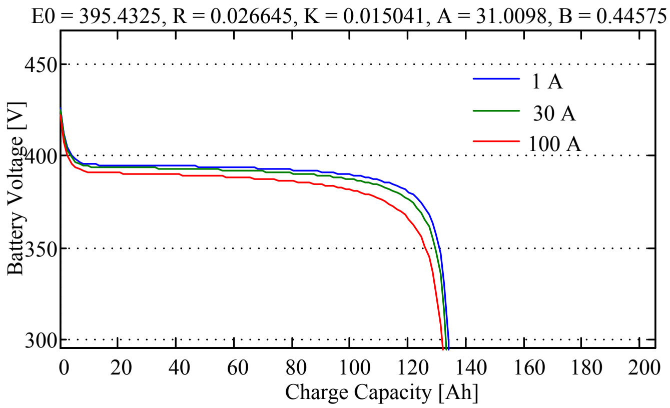

Fig. 5. Battery discharge characteristics.

III. POWER ELECTRONICS MODELING

A single-phase full-bridge inverter interfaces the used vehicular batteries to the 240V AC network, forming the proposed community energy storage system as shown in Fig. 6. The control system receives the measurements from the system such as the grid voltage, grid current, load voltage, load current, battery state-of-charge (SOC), breaker signal from the distribution substation for outages, and the ancillary service signal commands from the independent system operator (ISO), aggregator, or the local utility that controls the community energy storage systems.

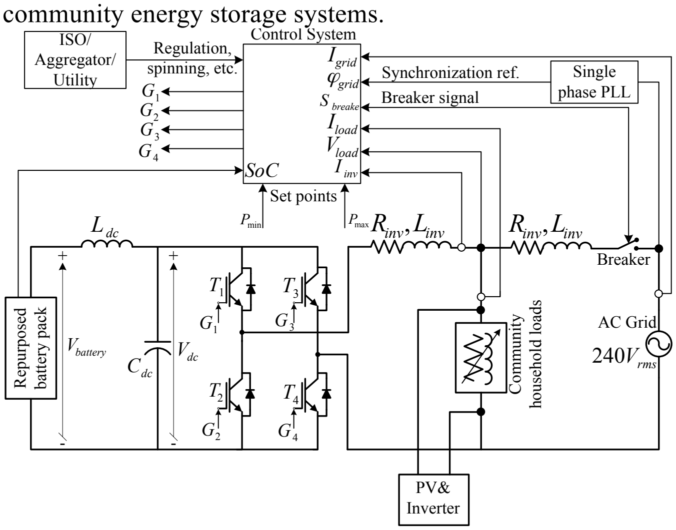

Fig. 6. Single phase inverter with battery, load, and grid interface.

The proposed applications of the CES covers; time of use energy management (peak shaving for local loads), load factor improvement (load leveling), contributing to the area frequency regulation or providing spinning/non-spinning reserves with the commands from ISOs or utility, and providing electric service reliability (emergency backup power supply). The overall control system for these applications is illustrated in Fig. 7.

The control system of the inverter, according to the measurements and received signals, makes the decision to recharge or discharge the used battery pack at appropriate power levels. According to the reference charge/discharge power and the AC link voltage, a hysteresis based current control strategy is implemented within the control system that accommodates the existing needs as shown in Fig. 7 [7].

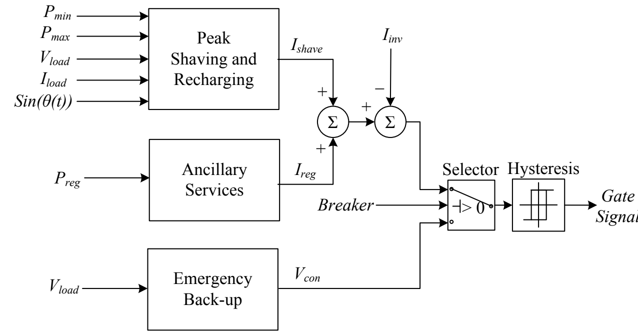

Fig. 7. Control system for inverter.

When a power outage or when a under voltage/over voltage event occurs [8], control system switches from current control mode to the voltage control mode in order to provide a fixed 240V AC power to the loads as shown in Fig. 8. During the time of an outage, no other ancillary services could be provided to the grid since there is no existing grid connection. A single-phase phase-lock loop (PLL) system is employed to detect the grid's voltage phase angle so that the current injected to the grid can be made in phase with the grid's voltage to avoid any reactive power or power factor issues, especially when recharging the battery pack during off-peak demand periods.

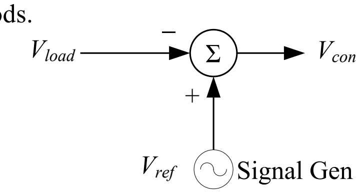

Fig. 8. Emergency backup power control.

For load factor improvement, an approach with set-points P_{max} and P_{min} is utilized as shown in Fig. 9 and Fig. 10. When the load power exceeds P_{max}, the battery is controlled to provide the excess power to the residential unit while ensuring the power factor does not fall below the required level. In this way, grid power can be levelized at P_{max}. To control the power factor the reactive power injected by the inverter is calculated as follows:

$$Q_{inv} = Q_L - (P_L - P_{inv})(\tan(\cos^{-1}(pf)) \tag{3}$$

where P_{inv} and Q_{inv} are the injected real and reactive power of inverter [W] [Var], P_L and Q_L are the real and reactive power consumed by the load [W] [Var], and pf is the objective power factor. When the home load demand is less than P_{min} set point, the battery pack can be recharged and still maintain the required power factor. Therefore, the home load consumption can be maintained between P_{min} and P_{max} with improved load factor. The inverter injected real power is based on the input from Table II.

TABLE II
INVERTER POWER CRITERA

Power Load Criteria	Total
$P_L > P_{max}$	$P_{inv} = P_L - P_{max}$
$P_L < P_{min}$	$P_{inv} = P_{min} - P_L$

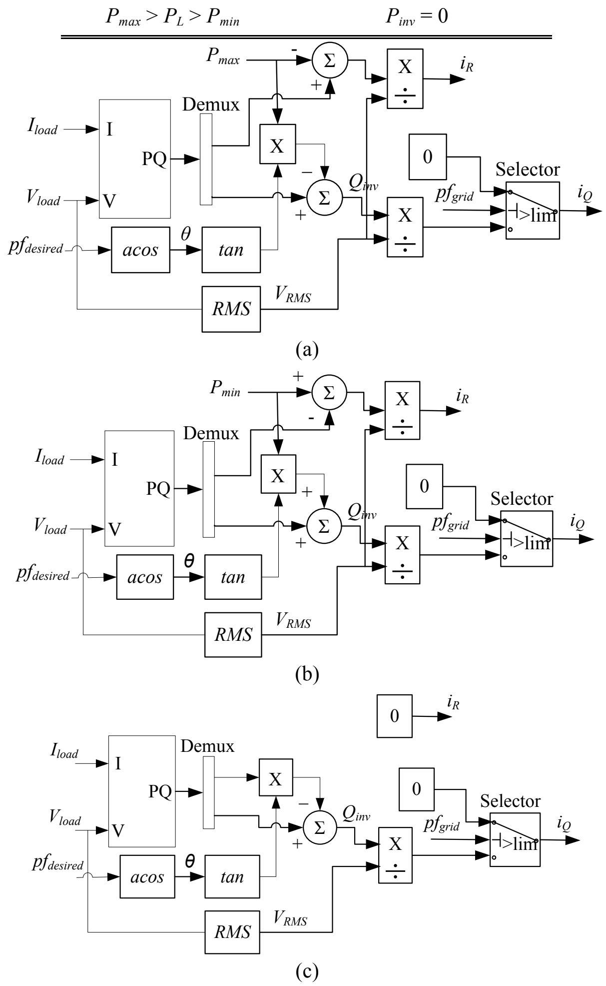

Fig. 9. Calculation of injected real and reactive power values; (a) discharging for reducing peak, (b) charging based on minimum, and (c) no power delivery.

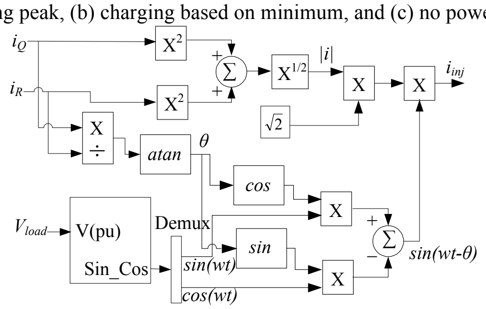

Fig. 10. Calculation of injected current.

When providing ancillary services, it is assumed that an aggregator or utility sends the reference power signals to the CES as shown in Fig. 11. This signal could represent either contingency reserves or frequency regulation.

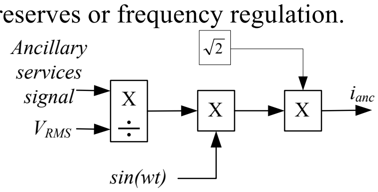

Fig. 11. Ancillary services control.

The description above represents the control and methodology for response of a single storage system. However, applying this switching control and approach in evaluating a system of units within a distribution system in this detail requires significant computation time for evaluation due to the power electronic switching. A more basic model for the CES units has also been created to perform longer period runs to demonstrate the aggregated effect of CES units over single days as shown in Fig. 12. The second model or aggregated model is achieved by simplifying the inverter dynamics through a transfer function model.

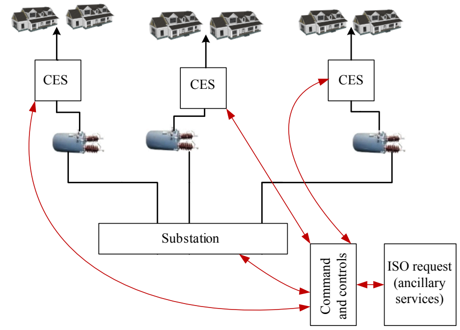

Fig. 12. Aggregated model of multiple CES units.

For dispatching the CES units in more optimized fashion and to remain in the bounds of the state of charge (SOC) of the energy storage systems, a linear control approach for dispatching the energy storage system was applied to the basic model. The individual available SOC for a single battery is divided by the total available SOC from all of the batteries as shown in Fig. 13. This is the ratio of delivered energy from the individual battery. In this way, the batteries with the higher values of available SOC, having the highest net SOC to share, are utilized to deliver the most energy during discharging and the batteries with the lowest SOC, having the highest net SOC to accept, are dispatched to absorb the most energy during charging.

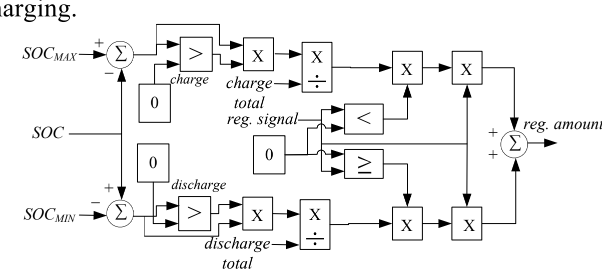

Fig. 13. SOC optimization.

IV. Results

For demonstration of the controls of the power electronics for the CES units several example simulations using the detailed model were conducted. The first simulation involved running several load steps such that the load was below the minimum, between the minimum and maximum, and above the maximum. The load was also adjusted in terms of power factor to demonstrate the capability to deliver the required reactive power to ensure that the interconnected power system sees only a high power factor. In this case, the load is set to consume 1.52kW, 9.12kW, and 19.7kW at 0.9 pf as shown in Figs. 14 and 15 where P_{min} and P_{max} are set to 6kW and 15kW respectively. The P_{min} and P_{max} values are expected to be command and control from the substation to reduce the impact of residential loading on the substation transformer and equipment. The target minimum power factor is 0.97. In this results, load power is positive since it is a consumer, grid power is negative since it is a supplier, and the inverter power is either negative or positive, depending on the operation mode.

During the first 2 seconds, the load power is below the minimum of P_{min} and the energy storage system is controlled to act as a load to increase consumption seen by the grid up to 6kW. Due to the high power versus reactive power consumption, the interconnection appears with a high power factor without the support of reactive power as shown in Fig. 15 and Fig. 16. During the following 2 seconds, the power level is between the P_{min} and P_{max} setpoints and no additional power is needed. However, reactive power is required to increase the power factor from 0.90 to 0.97 as shown in Fig. 15 and Fig. 16. Finally, during the following 2 seconds, the power level of the load is higher than P_{max} requiring that the load deliver both real and reactive power to maintain the grid at P_{max} with a power factor of 0.97.

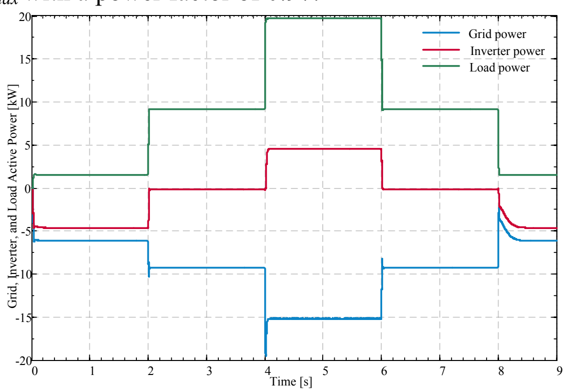

Fig. 14. Real power from interconnected grid, load, and injected by inverter.

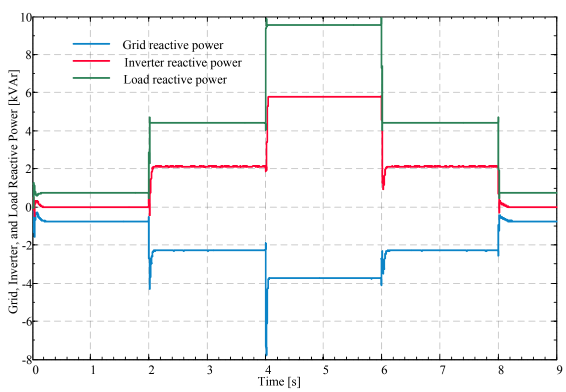

Fig. 15. Reactive power from interconnected grid, load, and injected by inverter.

In evaluating the effectiveness of the emergency backup control, the voltage on the grid interconnection was dropped to 0.85pu from t=0.5s to t=2s. From the control, the breaker is opened and the CES supplies the required power to follow the load. The result of this simulation is shown in Fig. 17 whereas Fig. 18 shows the voltage recovery during the outage. Finally, to demonstrate the command and control from the ISO, a dispatch signal is sent to the CES unit and the response of the CES unit is shown in Fig. 19.

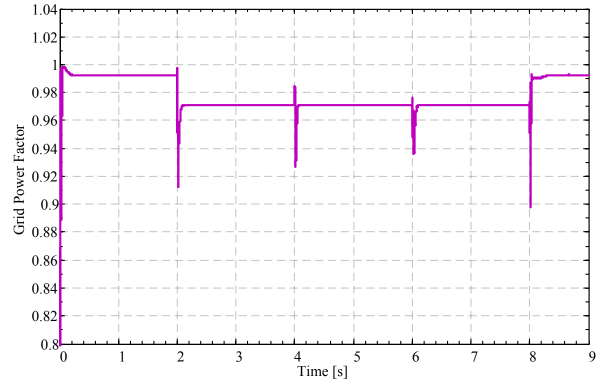

Fig. 16. Grid power factor.

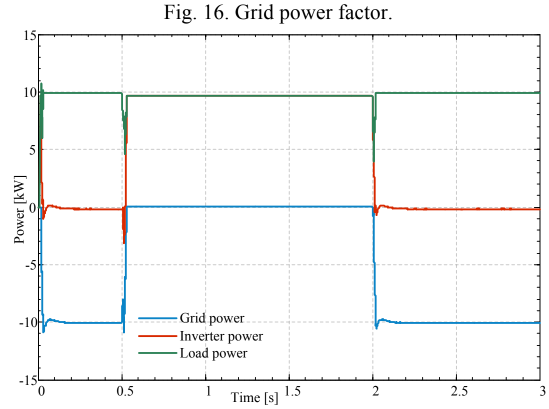

Fig. 17. Back-up power from CES during outage.

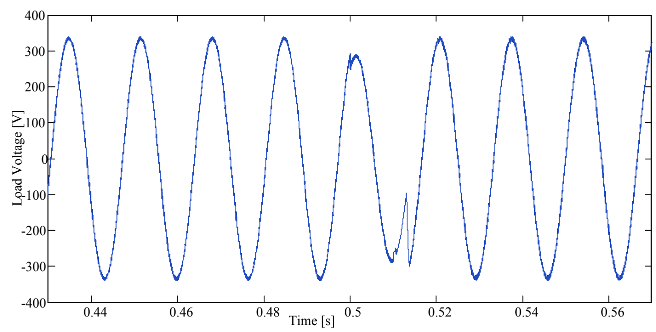

Fig. 18. Voltage recovery during the outage.

To demonstrate the aggregated effect and control, five separate CES units with 5 residential load data sets are simulated. Fig. 20 and Fig. 21 show the grid and load power results and SOC of the CES units respectively. From Fig. 20, there is a clear indication that the CES units were able to provide significant peak reduction. On a distributed and larger scale, CES units could provide significant peak reduction. Fig. 21 shows that the SOC for each CES remained between 80 and 45%. These limits could be improved with reduced impact on peak reduction.

For demonstration of ancillary services, a regulation signal is utilized and how the aggregated CES units responded to this signal is shown Fig. 22. Here, a portion of a typical ancillary service signal, which is a pulse power for 5 seconds, has been implemented. Only a portion (6%) of the CES rating is utilized in this case to provide this service. The SOC optimization technique is able to adjust the SOC of each CES unit near the set medium of 55% as shown in Fig. 23.

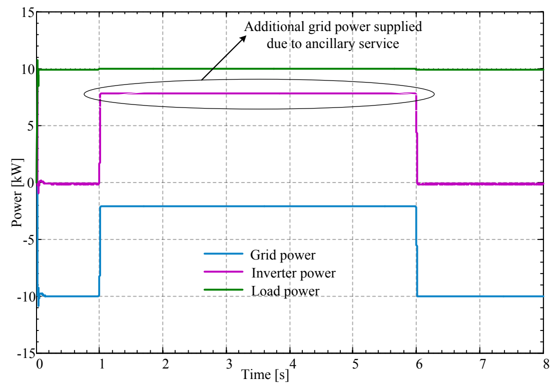

Fig. 19. CES unit responding to ISO request.

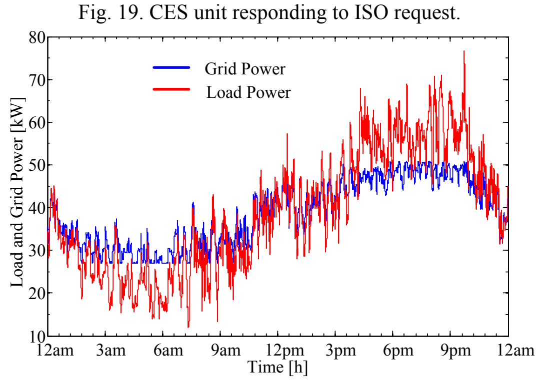

Fig. 20. CES units providing aggregated peak shaving.

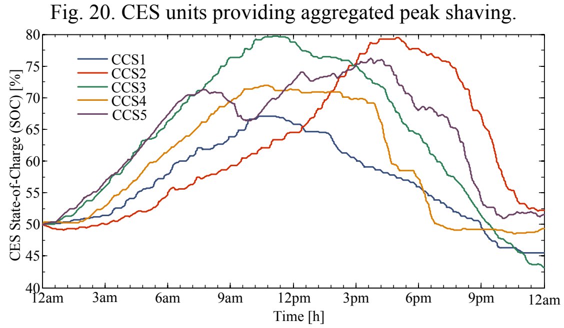

Fig. 21. CES SOC during peak shaving.

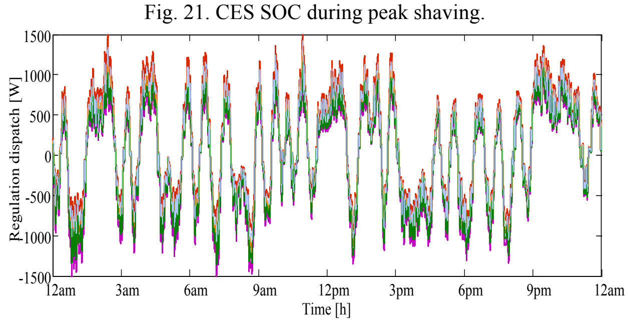

Fig. 22. CES' regulation dispatch variation.

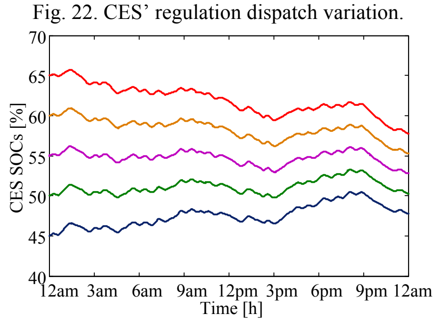

Fig. 23. CES SOC variations during responding to ISO command signal.

V. Conclusions and Future Work

This study represents a community energy storage system composed of repurposed vehicular batteries and a full-bridge inverter along with its control system in order to support the residential load, grid, and to provide grid ancillary services. Detailed simulations of the control are provided along with a more basic model for demonstrating the aggregated impact of many CES units on a distribution system.

Future work will involve the incorporation of renewable resources and PHEV type loads in the simulation. Furthermore, future work will incorporate results of testing on actual unit.

VI. Acknowledgements

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